

Looking for Squark Pair Production in the Early LHC Data

Z. Usubov*

Joint Institute for Nuclear Research,
Dubna, Russia

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Abstract

We examine the ability of LHC experiments to observe jets from squark pair production at the center-of-mass energy $E_{CM}=10$ TeV and 1 fb^{-1} of integrated luminosity. We point out the crucial influence of initial- and final-state radiation on the signal/background discriminating ability of different kinematic variables. The reliable measurements of missing transverse energy and stransverse mass would play a key role in picking out the signal against the background.

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1 Introduction

Among many exciting challenges that the Large Hadron Collider (LHC) era brings most difficult is to build of the fundamental theory to describe the physics at arbitrary high energies. Supersymmetry (SUSY)[1] is regarded as a widely favored candidate.

SUSY with beautiful mathematical grace is good almost in all senses: the quadratically divergent contributions to the scalar sector are canceled, the light Higgs boson is predicted, the SUSY particle spectra contain the dark matter candidates. SUSY allows the unification of all known fundamental forces and,

*On leave of absence from Institute of Physics, Baku, Azerbaijan

presumable, allows explanation of baryon asymmetry in the universe, superstring theory naturally incorporates SUSY.

To exclude some unwanted superpotential terms and provide the proton longevity the SUSY theories are usually supplied with discrete symmetry – R-parity conservation[4]¹. As a consequence, the SUSY superpartners of the Standard Model (SM) particles are produced in pairs and decay to a SM particle and the lightest supersymmetric particle (LSP). The LSP is neutral, stable and weakly interacting and usually identified as the lightest neutralino or gravitino escaping the detector unseen.

Unfortunately, the origin of SUSY breaking is not enough explored yet. The parametrization of soft SUSY breaking in supersymmetric Lagrangian density is now the basis of many models used in SUSY searches in collider experiments. Among them are the models with graviton, gauge and anomaly mediated soft SUSY breaking terms. Soft parameters can be determined from the LHC and ILC data if SUSY is discovered.

The most popular SUSY breaking mechanism is realized in minimal supergravity (mSUGRA)[5], where the SUSY breaking mediated from "hidden" to the "visible" sector by gravitational interactions. These models are strongly motivated, consistent with experimental data, and simple enough to explore in current collider experiments². In mSUGRA five parameters, four continuous and one discrete,

$$m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu),$$

are enough to calculate superpartner masses and mixings. Here m_0 is the common mass for scalars, $m_{1/2}$ is the common gaugino mass, A_0 is the common soft trilinear SUSY breaking parameter, $\text{sign}(\mu)$ is the sign of the Higgsino mass term, $\tan\beta$ is the ratio of the vacuum expectation values of two Higgs doublets giving mass to the up and down type quarks. The parameters m_0 , $m_{1/2}$, A_0 are defined at the grand unification scale and $\tan\beta$ at the electroweak scale. Note that low-energy parametrization of the Minimal Supersymmetric Standard Model contains up to 120 parameters arising mainly in the soft symmetry breaking terms.

Intensive searches for manifestation of SUSY at the Tevatron were performed by CDF and D0 collaborations (see e.g. Ref. [7] and refs therein). The LEP

¹The KK-parity conserving universal extra dimension[2] models and little Higgs[3] models with conserved T-parity as extensions of the Standard Model, predicts their own candidates for dark matter.

² About some problems in mSUGRA and its solutions see e.g. Ref. [6].

and HERA Collaborations also looked for SUSY in a variety of channels (see Refs. [8, 9]).

The ATLAS and CMS experiments have developed search strategies[10, 11] covering different SUSY breaking schemes and event topologies.

At the hadron colliders the inclusive production of squarks and gluinos via strong interaction dominate over associated production of charginos and neutralinos and is one of the most promising discovery channels for SUSY.

In this paper, we restrict ourselves to the study of the squark pair production in pp collisions at the center-of-mass energy $E_{CM} = 10$ TeV. This channel suffers from high backgrounds from QCD jet events. The requirement of high missing transverse energy values effectively rejects this background. We will also focus on the azimuthal angle between two hardest jets, the variables m_{T2} [12] and α [13]. To eliminate multistep cascade decays of squarks we choose the parameter point of mSUGRA where squarks are lighter than the gluinos. In this case, the primary decay modes are $\tilde{q} \rightarrow q\tilde{\chi}_i^0$. Thus, the squark pair will be presented in the interaction products as two quarks and two neutralinos. The final state exhibits missing energy and no mass peaks can be directly reconstructed.

In addition to the QCD events, the main background to SUSY dijet signatures are electroweak processes such as $W + jets$, $Z + jets$, $t\bar{t} + jets$ events. We find that the diboson production rate in the background is negligibly small for this study.

The rest of this paper is organized as follows. The next section gives a brief description of signal and background events, the choice of the SUSY benchmark point and some parameters of the generic LHC detector. Section 3 gives our strategy for the search for SUSY dijet events. We make use of different kinematic variables and examine signal and background events. In this Section we also make an estimate of the $\tilde{q}\tilde{q}$ signal-to-background ratio. The impact of the calorimeter energy resolution, initial- and final-state radiation and jet reconstruction algorithm to the dijet variable distributions are studied. We end with the conclusions in Section 4.

2 Signal and Standard Model background simulations for the generic LHC detector

In order to study the ability of the LHC to observe the SUSY dijet events at $E_{CM} = 10$ TeV we used the PYTHIA6.4[14] event generator for signal and QCD background simulation. The ALPGEN2.12[15] code was used for $tt + nj$, $W + nj$, $Z + nj$ and diboson samples, where nj denotes n light jets. It was interfaced with PYTHIA for subsequent jet showering and hadronization. We include the following processes in our background analysis: 0-2 jets in tt , 0-3 jets in Z and 0-4 jets in W events. Only in one diboson (ZZ, ZW, WW) event for 1 fb^{-1} of data set the sum of the transverse momenta of two hardest jets becomes greater than 500 GeV (see below).

For this analysis, we used the mSUGRA scenario with the commonly used SPS1a'[16] benchmark point. The model parameters at this point are $m_0 = 70$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$. We used the SPheno[17] package for calculating the sparticle mass spectra, decay widths and branching ratios. The benchmark point used lead to a SUSY particle spectrum with $m_{\chi_0^1} \sim 98$ GeV, $m_{\tilde{q}} \sim 550$ GeV, $m_{\tilde{g}} \sim 608$ GeV. The total leading-order cross section of squark pair production at this point is ~ 4.65 pb if the transverse momentum of the outgoing partons in the hard scattering process is greater than 50 GeV.

We use the central values of leading-order parton distribution function set from CTEQ6L1[18] and do not change the PYTHIA6.4 default choices for Q^2 definition as well as factorization/renormalization scales. The initial- and final-state QCD and QED radiation (IFSR) and multiple interactions (MI) were enabled.

The detector performance was simulated by using the publicly available PGS-4[19] package written by J. Conway and modified by S. Mrenna for the generic LHC detector. The calorimeter granularity is set to $(\Delta\phi \times \Delta\eta) = (0.10 \times 0.10)$. Energy smearing in the hadronic calorimeter of the generic LHC detector is governed by³

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b \quad (E \text{ in GeV}),$$

where the stochastic term factor is $a = 0.8$ and the constant factor is $b = 0.03$.

³We add the constant term to the PGS-4 simulation of energy smearing in the hadronic calorimeter.

Jets were reconstructed down to $|\eta| \leq 3$ using the k_T algorithm implemented in PGS-4. We chose $D = 0.4$ for the jet resolution parameter and required that both leading jets carried a transverse momentum $p_T^{1,2} > 50$ GeV.

In order to suppress backgrounds from the semileptonic SM and SUSY processes we select events without any isolated muon, electron, tau or photon with $p_T > 20$ GeV. We use the simplified output from PGS-4, namely, a list of two most energetic jets.

We simulated signal and background events at the rates corresponding to 1 fb^{-1} of accumulated data. We note that the K-factor is ~ 1.8 - 2.0 for QCD

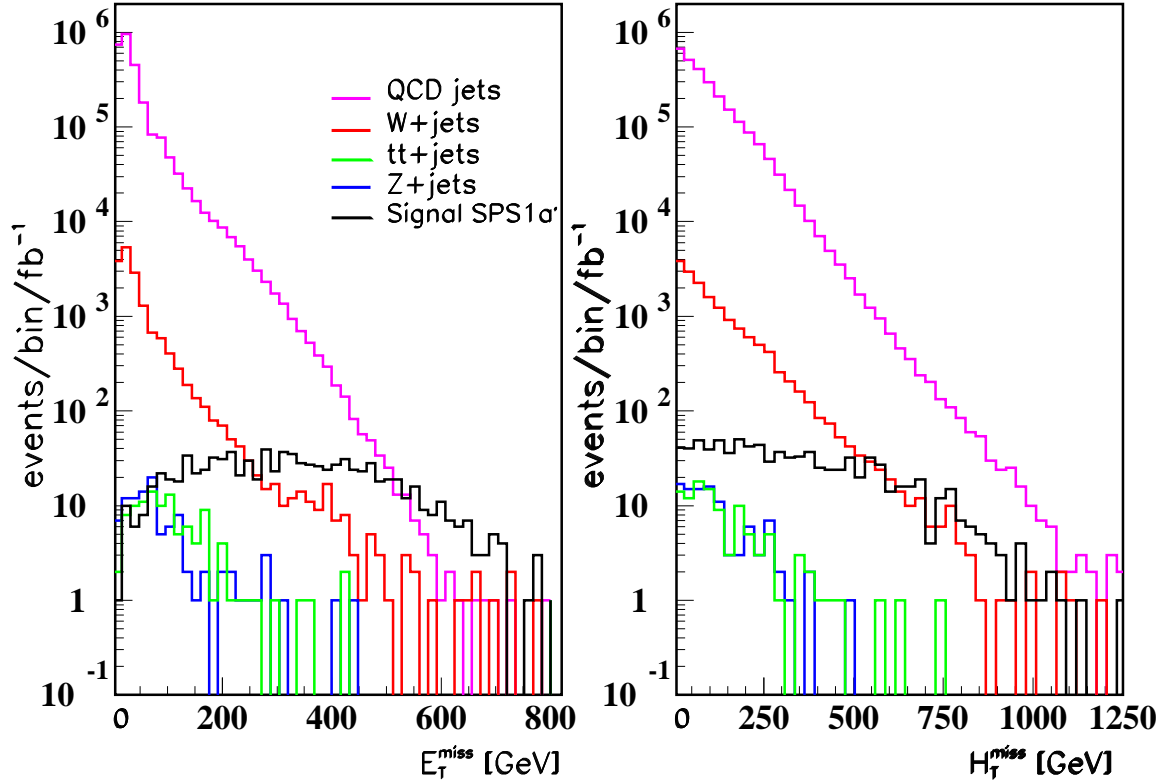


Figure 1: Distributions of the E_T^{miss} (left) and H_T^{miss} (right) variables (see the text) for the signal and background events at $E_{CM} = 10$ TeV and integrated luminosity of 1 fb^{-1} and the SPS1a' benchmark point. The sum of the transverse momenta of two hardest jets satisfies $p_T^1 + p_T^2 > 500$ GeV.

background, ≤ 1.2 for $W + jets$ and $Z + jets$ [20], ~ 1.1 for $tt + 1j$ [21], and ~ 0.89 for $tt + 2j$ [22] events. The K-factor for the signal events at the benchmark point SPS1a' calculated with using Prospino2.1[23] is about 1.5. In this analysis no K-factor was applied and we recognize that our results on signal significance

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|--------------------|------|------|------|------|------|------|
| $E_T^{miss} [GeV]$ | 200 | 300 | 350 | 400 | 450 | 500 |
| S/B | 0.02 | 0.09 | 0.19 | 0.45 | 0.94 | 1.79 |

Table 1: The signal-to-background ratio for the $\tilde{q}\tilde{q}$ production in pp interactions at $E_{CM} = 10$ TeV and 1 fb^{-1} of integrated luminosity estimated at different selection cuts for E_T^{miss} .

may be overestimated.

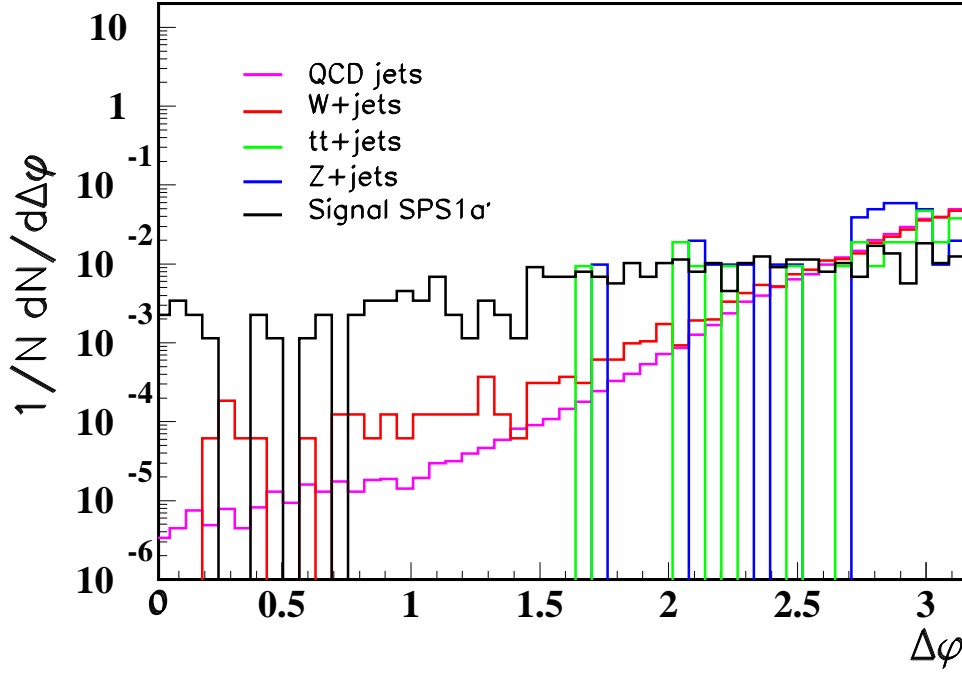


Figure 2: The normalized distribution of the difference of the azimuthal angles for two hardest jets ($p_T^1 + p_T^2 > 500$ GeV) for signal events along with various Standard Model background sources at $E_{CM} = 10$ TeV and 1 fb^{-1} of integrated luminosity.

3 Looking for squark pair production for one particular mSUGRA benchmark point

Even in the early stages of its operation the LHC allows one to reach very large values of the jet transverse energy, the region which has never been studied before.

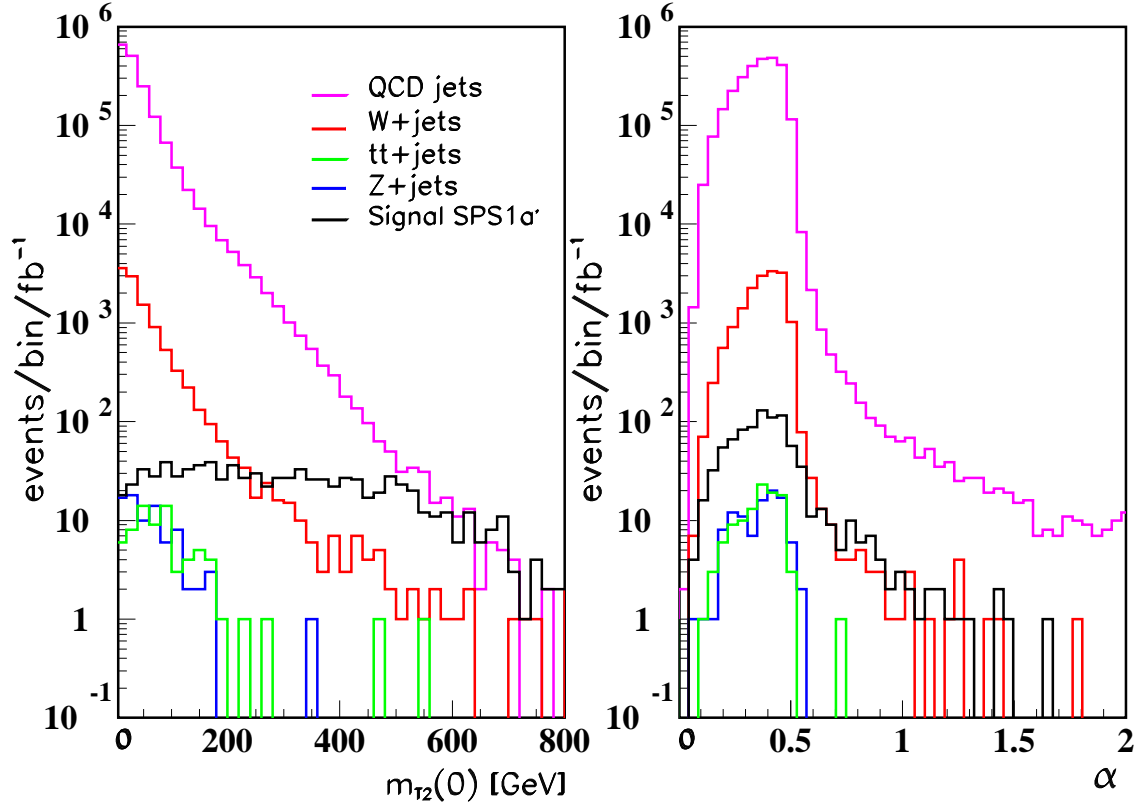


Figure 3: Expected distributions of the variables m_{T2} (left) and α (right) for the signal and background events at $E_{CM} = 10$ TeV and integrated luminosity of 1 fb^{-1} and SPS1a' benchmark point.

We start with comparing the missing transverse energy E_T^{miss} of the whole event and H_T^{miss} defined using only two leading jets in the event. In Fig. 1 we plot signal and background events binned in E_T^{miss} and H_T^{miss} . The only selection criterion requires a hard cut of 500 GeV on the sum of the transverse momenta of two hardest jets. A comparison of the left and right panels of Fig. 1 shows that the effectiveness of background restrictions based on the E_T^{miss} and H_T^{miss} cuts would significantly differ towards high values of these variables. In Table 1 we present the signal-to-background ratio, S/B, for different selection cuts for E_T^{miss} . It would be possible to achieve the signal significance⁴ $S/\sqrt{S+B}$ of about 10.5 with the accumulated data of 1 fb^{-1} using only the E_T^{miss} cut. With only the cuts on H_T^{miss} it is impossible to get signal significance even close to 3.

Besides being of physics origin, events with the missing transverse energy also have other sources. Mismeasurements of the energy of jets, incomplete

⁴ We follow the tradition but can say that if no robust signature in the mass peak is observable, the use of this signal significance is not so compelling.

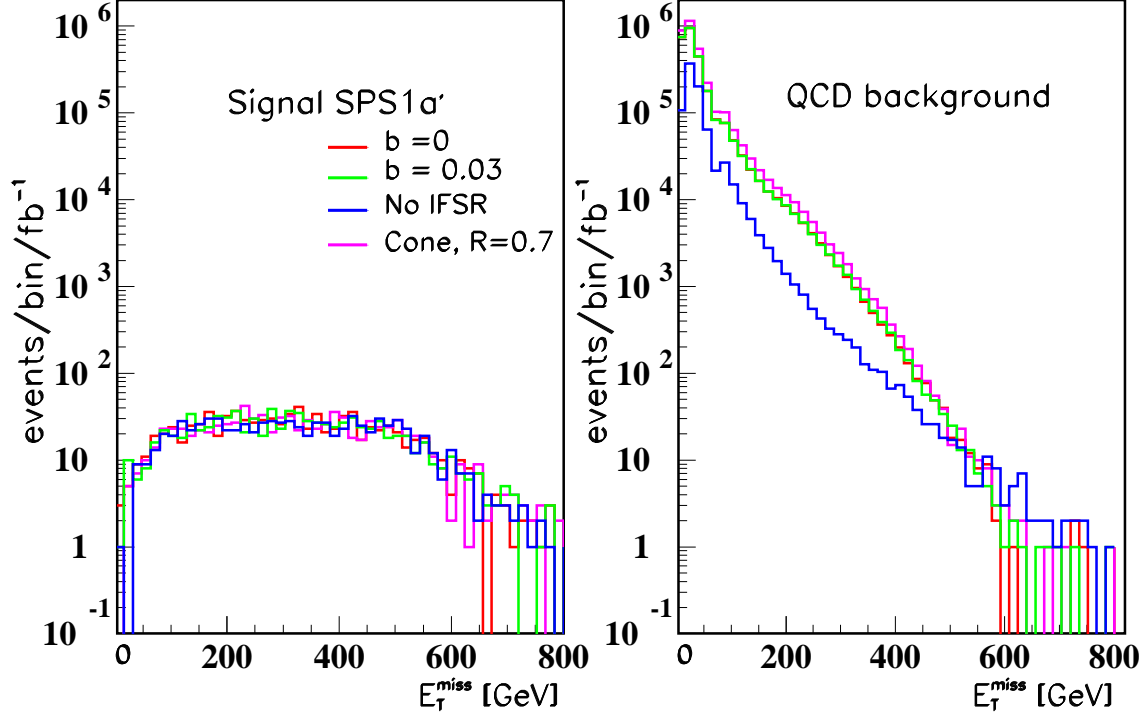


Figure 4: Expected E_T^{miss} distributions for signal events at the SPS1a' benchmark point (left) and QCD background events with and without initial- and final-state radiation, for different constant terms b in the hadron calorimeter resolution expression, and with the jet cone algorithm (right). LHC operation at $E_{CM} = 10$ TeV and integrated luminosity of 1 fb^{-1} is assumed.

coverage of the calorimeters, large electronic noise, etc. would lead to a large E_T^{miss} signal. For this reason, in the early stage of the LHC running it may not be possible to use E_T^{miss} as a signal/background discrimination variable. In what follows we do not implement any E_T^{miss} requirement.

The dijet angular distribution is a useful measurement to probe the SM processes as well as new physics manifestation. In Fig. 2 we plot the normalized dijet angular distribution, $1/N dN/d\Delta\phi$, where $\Delta\phi = \phi_1 - \phi_2$ for two leading jets. The signal event distribution is nearly flat in contrast to the background event distributions.

An important quantity which in principle allows observing squarks and determining their masses and masses of their invisible decay products is the m_{T2} [12]. Inspired by the transverse mass m_T in the $W \rightarrow l\nu$ decay this variable is sometimes called the stransverse mass. For the decay of two massive identical invisible particles m_{T2} is defined as

$$m_{T2}(\mu_N) \equiv \min_{p_T^1 + p_T^2 = p_T^{miss}} \{ \max[m_T^1(p_v^1, \not{p}_T^1, \mu_N), m_T^2(p_v^2, \not{p}_T^2, \mu_N)] \}.$$

| | | | | | | |
|----------------|-------|------|------|------|------|------|
| $m_{T2} [GeV]$ | 200 | 300 | 350 | 400 | 450 | 500 |
| S/B | 0.027 | 0.10 | 0.19 | 0.35 | 0.54 | 0.74 |

Table 2: The signal-to-background ratio for the $\tilde{q}\tilde{q}$ production in pp interactions at $E_{CM} = 10$ TeV and 1 fb^{-1} of integrated luminosity estimated at different selection cuts for m_{T2} .

Here $p_v^{1(2)}$ are the sum of the momenta of the visible decay products of a parent particles, μ_N is the trial mass parameter, namely, the mass of the LSP and $m_T(p_v, p_i, m_i) = m_v^2 + m_i^2 + 2(E_{vT}E_{iT} - \vec{p}_{vT}\vec{p}_{iT})$, $E_{i(v)T} = \sqrt{\vec{p}_{i(v)T}^2 + m_{i(v)}^2}$. The minimization is taken over all possible missing energy p_T^{miss} splittings.

In Fig. 3 (left panel) we demonstrate the m_{T2} distribution for events with the sum of the transverse momenta of two hardest jets greater than 500 GeV. For this calculations we assume the massless LSP. The S/B for different m_{T2} cuts

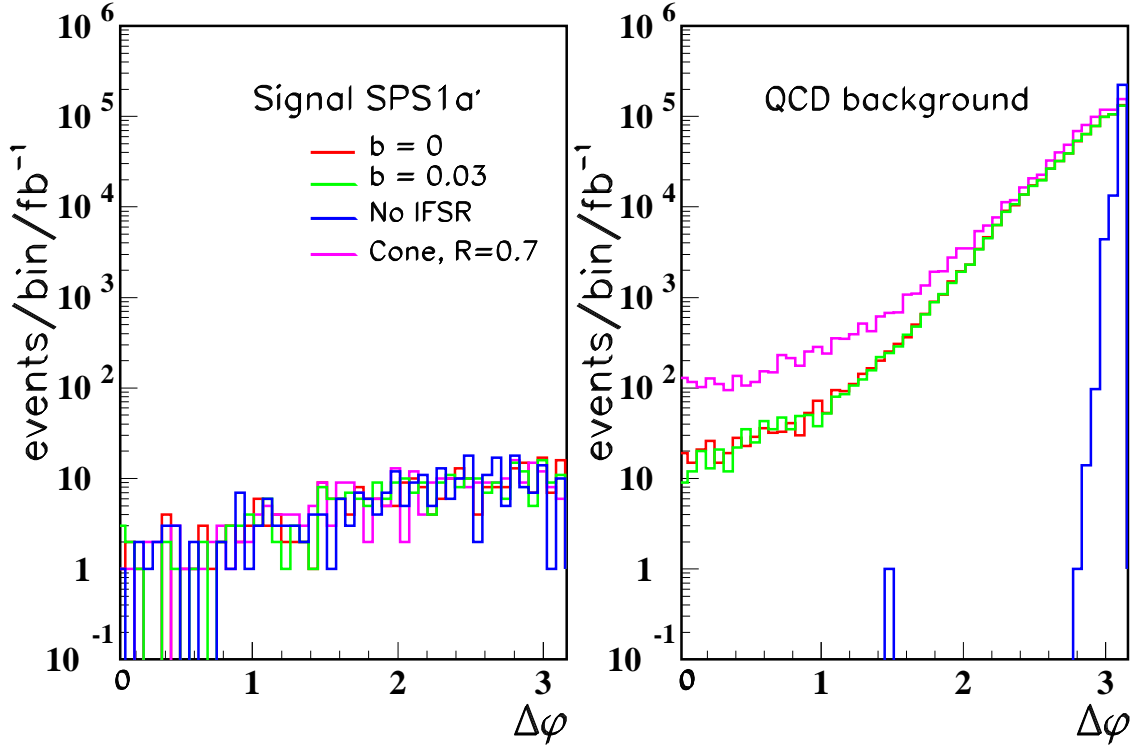


Figure 5: Same as in Fig. 4 but for the difference of the azimuthal angles of two hardest jets.

is presented in Table 2. The signal significance of 8.2 is achievable using the m_{T2} cut alone and ~ 10 with the combination of m_{T2} and E_T^{miss} . The tandem of H_T^{miss} and m_{T2} does not lead to improvement of the signal significance.

We find that $0.25(0.4)\text{fb}^{-1}$ of an integrated luminosity when the LHC runs at

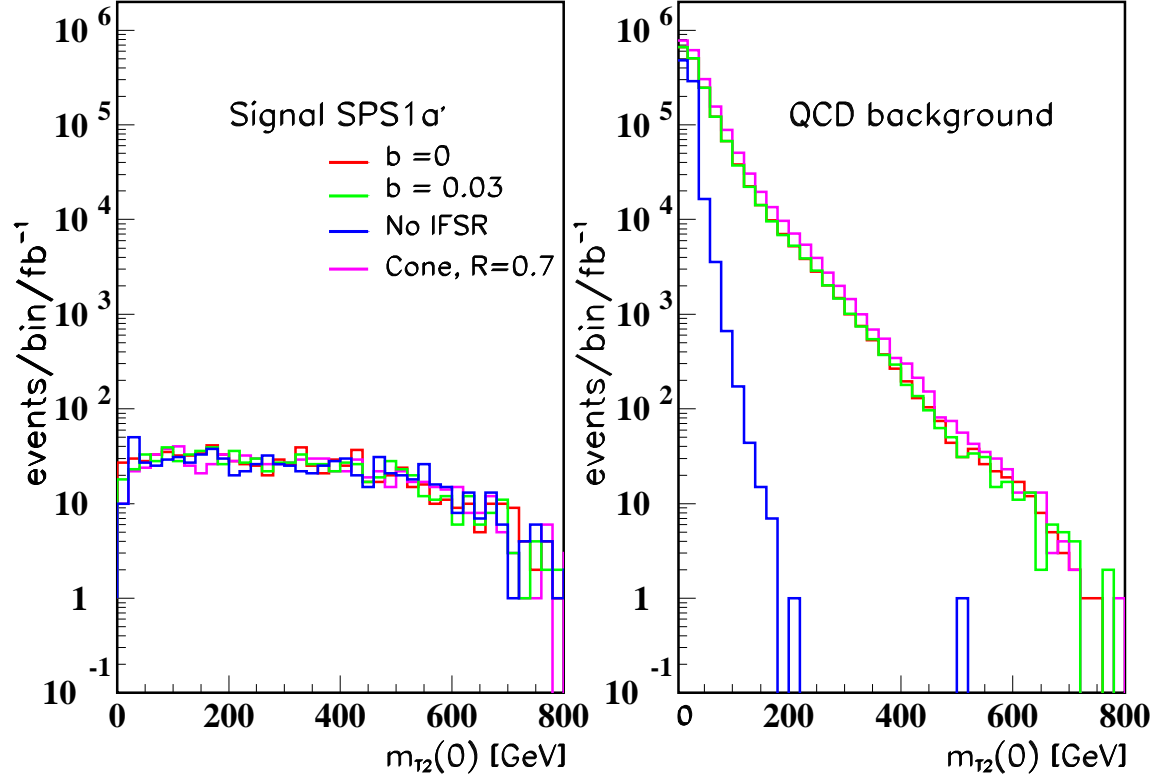


Figure 6: Same as in Fig. 4 but for m_{T2} distribution.

$E_{CM}=10$ TeV would provide observation of the $\tilde{q}\tilde{q}$ signal with 5 standard deviations of statistical uncertainty using the $E_T^{miss}(m_{T2})$ distribution. Further, we estimate that a factor of ~ 2.3 less integrated luminosity is required at 14 TeV, and a factor of about 2.5 more at 7 TeV, to achieve the same signal sensitivity as at 10 TeV.

Recently, the new measurable α [13] has been proposed which can be used as a signal/background discriminating variable in squark pair production. This analysis does not explicitly require the E_T^{miss} cut. The variable α is defined as the ratio of the second hardest jet transverse momentum to the invariant mass $m_{inv}^{1,2}$ of two hardest jets

$$\alpha = \frac{p_T^2}{m_{inv}^{1,2}}.$$

In Fig. 3 (right panel) we show the α distributions for the signal and background events. As one can see, the clean SUSY signal at larger α values is not viable due to a bigger tail of the QCD background distribution. The $\alpha > 0.6$ signal is 45 times weaker than the SM background.

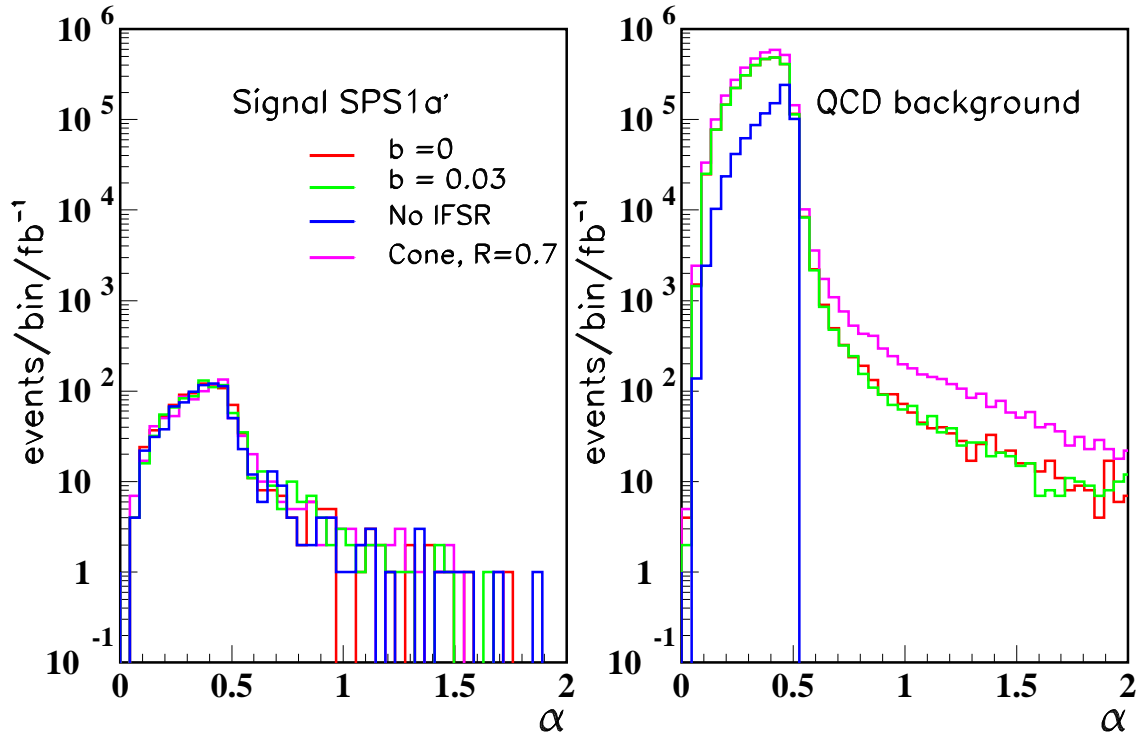


Figure 7: Same as in Fig. 4 but for α distribution.

To get further insight, in Figs. 4-7 we show what happens with the E_T^{miss} , $\Delta\phi$, m_{T2} and α distributions of the signal and QCD background events when IFSR are switched off in the simulated events. The impact of the constant term b in the calorimeter energy resolution formula and jet definition algorithm is also demonstrated in these figures. The cyan histogram in the figures corresponds to the cone jet definition algorithm with the cone radius $R = 0.7$. The signal event distributions are robust to all these influences. The presence of IFSR significantly increases the QCD background for all these distributions at large values of the E_T^{miss} , m_{T2} and α and small values of $\Delta\phi$. We can see that the missing transverse energy for the QCD background at large values of E_T^{miss} is less susceptible to the IFSR. The impact of the MI on the m_{T2} distribution of the signal events is demonstrated in Fig. 8. One can see that the upper edge of these distributions indicates to the mass of the parent squark. The experimental resolution leads to the smearing of the correct mass point.

Finally, we remark that the behavior of the α distribution of the QCD background without IFSR in Fig. 7 looks surprisingly like the ones obtained in Refs. [13, 24].

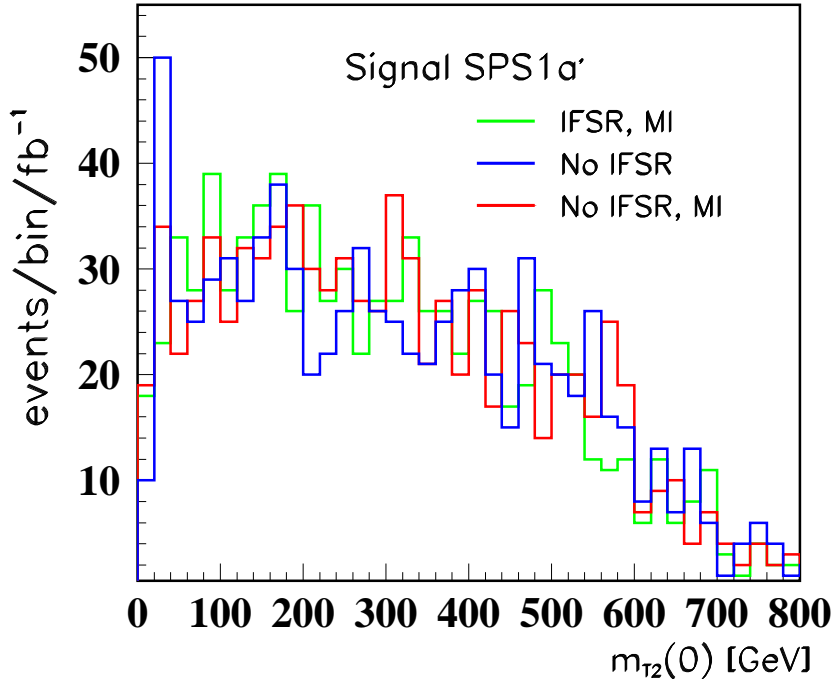


Figure 8: Expected m_{T2} distributions for signal events with initial- and final-state radiation and multiple interactions and without them when the sum of the momenta of two hardest jets is greater than 500 GeV. The data correspond to 1 fb^{-1} of integrated luminosity at $E_{CM} = 10 \text{ TeV}$.

4 Conclusions

We have demonstrated that squark pair production in pp collisions at the center-of-mass energy of $E_{CM} = 10 \text{ TeV}$ is a promising channel for discovery of SUSY at the early stages of LHC running. Our attention was focused on the distinctive characteristics of background subtractions in $\tilde{q}\bar{\tilde{q}}$ production for the mSUGRA benchmark point SPS1a' where the squarks are light.

With 1 fb^{-1} of integrated luminosity, strong evidence for a $\tilde{q}\bar{\tilde{q}}$ can appear with hard cuts on the missing transverse energy and transverse mass distributions. In the mSUGRA model with a benchmark point SPS1a' it is possible to reach a signal significance 5σ of statistical uncertainty with 0.4 fb^{-1} of accumulated data when LHC operates at $E_{CM} = 10 \text{ TeV}$.

We find that initial- and final- state radiation forms a crucial background for the α distribution of the $\tilde{q}\bar{\tilde{q}}$ signal. It should be hard to pick out the signal against the background in SUSY dijet events using the measured α distribution

even with a tandem of other measurables. The variable α not can provide an obvious advantage for discovery of $\tilde{q}\tilde{q}$ as was stated previously.

The careful validation of the whole richness of new physics at the LHC will be possible with improvement of our understanding of the known physics.

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